

****FULL TITLE****

*ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION***

****NAMES OF EDITORS****

The blazar's divide and the properties of Fermi blazars

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Abstract. The LAT instrument, onboard the *Fermi* satellite, in its first three months of operation detected more than 100 blazars at more than the 10σ level. This is already a great improvement with respect to its predecessor, the instrument EGRET onboard the *Compton Gamma Ray Observatory*. Observationally, the new detections follow and confirm the so-called blazar sequence, relating the bolometric observed non-thermal luminosity to the overall shape of the spectral energy distribution. We have studied the general physical properties of all these bright *Fermi* blazars, and found that their jets are matter dominated, carrying a large total power that correlates with the luminosity of their accretion disks. We suggest that the division of blazars into the two subclasses of broad line emitting objects (Flat Spectrum Radio Quasars) and line-less BL Lacs is a consequence of a rather drastic change of the accretion mode, becoming radiatively inefficient below a critical value of the accretion rate, corresponding to a disk luminosity of ~ 1 per cent of the Eddington one. The reduction of the ionizing photons below this limit implies that the broad line clouds, even if present, cannot produce significant broad lines, and the object becomes a BL Lac.

1. The Fermi blazar sequence

The Large Area Telescope (LAT) on board the *Fermi Gamma Ray Space Telescope* (*Fermi*) revealed in the first three months of operation 57 flat spectrum radio quasars (FSRQs), 42 BL Lac objects, and 5 blazars with uncertain classification (Abdo et al. 2009a, hereafter A09; Foschini et al., these proceedings).

Ghisellini et al. (2009a) showed that the spectral index α_γ correlates with the γ -ray luminosity L_γ and that BL Lacs and FSRQs occupy different regions of the $\alpha_\gamma - L_\gamma$ plane. There is a rather well defined boundary between BL Lacs and FSRQs as shown in Fig. 1. Empty circles and squares correspond to BL Lac objects and FSRQs, respectively, while filled symbols indicate sources also detected in the TeV band. This correlation holds *despite* the large amplitude variability of blazars, especially at high energies. Examples of how variability can change the position of single sources in the $\alpha_\gamma - L_\gamma$ plane are shown in Fig. 1 by the segments connecting the locations of specific sources at different times. Note that several sources “move” orthogonally to the correlation defined by the ensemble of sources, i.e. they become harder when brighter (with the exception of 3C 454.3). The high and the low γ -ray states of single sources can be dramatically different, and this implies that the distribution in luminosity within each blazar class is largely affected by the variability of the sources.

The exceptional case of BL Lac itself is shown in the right panel of Fig. 1. Its γ -ray luminosity varied by two orders of magnitude. Moreover the slope of the high energy emission varied from $\alpha_\gamma \sim 0.7$ (peak above 10 GeV) during the

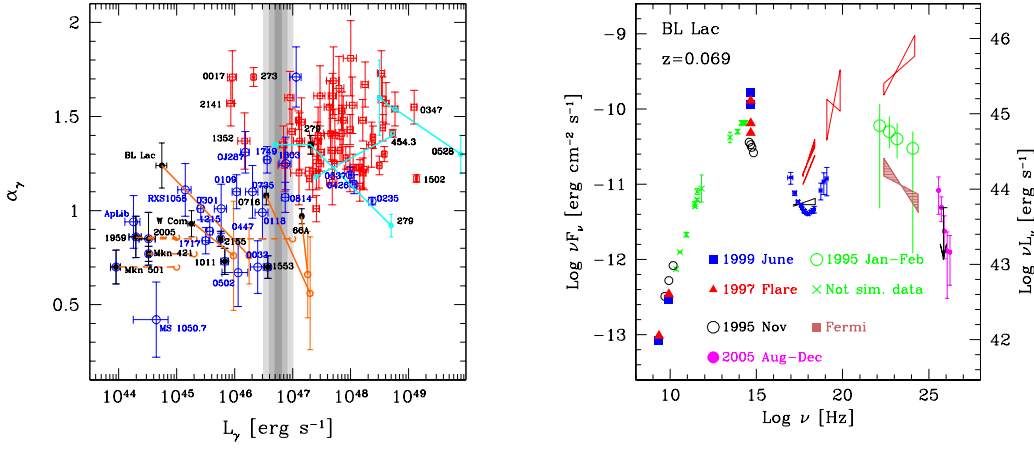


Figure 1. *Left panel:* energy spectral index vs γ -ray luminosity for all blazars in the list of A09. Empty squares and circles are BL Lacs and FSRQs, respectively. Filled symbols correspond to sources already detected in the TeV band. For a few blazars we show the observed range of γ -ray luminosity and spectral index, using past EGRET or *AGILE* observations. This is indicated by a segment. The grey stripes at about $L_\gamma = 10^{47} \text{ erg s}^{-1}$ mark the divide between BL Lac objects and FSRQs. *Right panel:* the SEDs of BL Lac itself illustrates the dramatic variability of blazars, especially at high energies.

1997 flare (Bloom et al. 1997), to the *Fermi*-observed value of $\alpha_\gamma \sim 1.2$ (peak around or below 100 MeV), corresponding to the lowest observed γ -ray state.

Fig. 1 shows that BL Lacs and FSRQs separate at $L_\gamma \sim 10^{47} \text{ erg s}^{-1}$, as indicated by the grey stripes. Furthermore there is a less clear-cut separation in spectral indices, occurring at $\alpha_\gamma \simeq 1.2$.

This behavior is just what the “blazar sequence” (Fossati et al. 1998; Ghisellini et al. 1998) would predict: low power BL Lac objects peak at higher energies, with the high energy peak often located beyond the LAT range: they have smaller L_γ and flatter α_γ . FSRQs, instead, peak at lower frequencies, and the peak of their high energy emission (dominating their power output) is below 100 MeV. In the LAT energy range they are steep, but powerful. Therefore the left panel of Fig. 1 represents the γ -ray selected version of the blazar sequence.

1.1. The divide

The other intriguing feature of Fig. 1 is the existence of a γ -ray luminosity dividing BL Lacs from FSRQs. We have proposed that this is a consequence of the change of the accretion regime, becoming radiatively inefficient below a critical disk luminosity, in units of Eddington. This reflects also in a critical (dividing) luminosity of the observed beamed emission, rather well tracked by L_γ . To understand why in a simple way, assume that most of the bright blazars detected by the 3-months LAT survey have approximately the same black hole mass. Assume also that the largest L_γ correspond to jets with the largest power carried in bulk motion of particles and fields. Finally, assume that the jet power and the accretion rate are related. These three assumptions, that will be better justified later, imply that the most luminous blazars have the most powerful jets

and are accreting near Eddington. These are the FSRQs with $L_\gamma \sim 10^{49} \text{ erg s}^{-1}$. The dividing L_γ is a factor 100 less, so it should correspond to disks emitting at the 1% level of the Eddington level. Below this value we find BL Lacs, that have no (or very weak) broad emission lines. If the disk becomes radiatively inefficient at $L_d < 10^{-2} L_{\text{Edd}}$ the broad line region receives a much decreased ionizing luminosity, and the lines become much weaker. The radiation energy density of the lines becomes unimportant for the formation of the high energy continuum (there are much less seed photons for the Inverse Compton process), implying: i) a reduced “Compton dominance” (i.e. the ratio of the Compton to synchrotron luminosities); ii) less severe cooling for the emitting electrons, that can then achieve larger energies and then iii) a shift of both the synchrotron and the Inverse Compton peak frequencies to larger values.

According to this interpretation, it is the accretion mode that determines the “look” of the radiation produced by the jet, not a property of the jet itself.

2. General properties of the *Fermi* blazars

We (Ghisellini et al. 2009b, hereafter G09) have studied and modelled almost all the *Fermi* blazars detected in its first 3-months of operation. We excluded objects without known redshift and a few with very few data available (insufficient to construct a meaningful SED). In total, we studied 85 blazars (including one Narrow Line Seyfert 1, see Abdo et al. 2009b, 2009c).

Many of them were observed by the X-ray (XRT) and UV-optical (UVOT) telescopes onboard *Swift*, and this was of great help in characterizing their SED. What was an exception in the EGRET era (and a result of huge efforts by many people involved in multi-wavelength campaigns) is now routine. Fig. 2 shows, for illustration, the SED of the FSRQ 2141+175. As can be seen, the synchrotron spectrum peaks at very low frequencies, and the flux produced by the accretion disk is well visible. In this case the data are good enough to fit the optical–UV flux with a standard Shakura–Sunjaev (1973) accretion disk. In turn, this allows to estimate the mass of the black hole and the accretion rate.

For these FSRQs (with good optical–UV coverage) we can then study in a reliable way the connection between the jet power and the accretion luminosity, also in units of the Eddington one. A first result is shown in the right panel of Fig. 2: the observed γ -ray luminosity L_γ is related with the accretion disk luminosity L_d . Note that for BL Lacs we have only an upper limit on L_d (shown by the triangles).

The grey stripe shows a linear relation above $L_d = 10^{45} \text{ erg s}^{-1}$ (with scatter, blazars can vary their non-thermal luminosity even by one or two order of magnitude). This is appropriate for all *Fermi* FSRQs. Below this critical luminosity value there are only BL Lacs, and the grey stripe becomes $L_\gamma \propto L_d^{1/2}$. This corresponds to assume that the jet power (and then the observed luminosity, for aligned sources) scales always as the accretion rate \dot{M} , while the disk luminosity, which is linear with \dot{M} at high rates, scales as $L_d \propto \dot{M}^2$ below $L_d = 10^{45} \text{ erg s}^{-1}$, so that $L_\gamma \propto \dot{M} \propto L_d^{1/2}$ (see Ghisellini & Tavecchio 2008). Note that, for a $10^9 M_\odot$ black hole, this “dividing” luminosity corresponds to

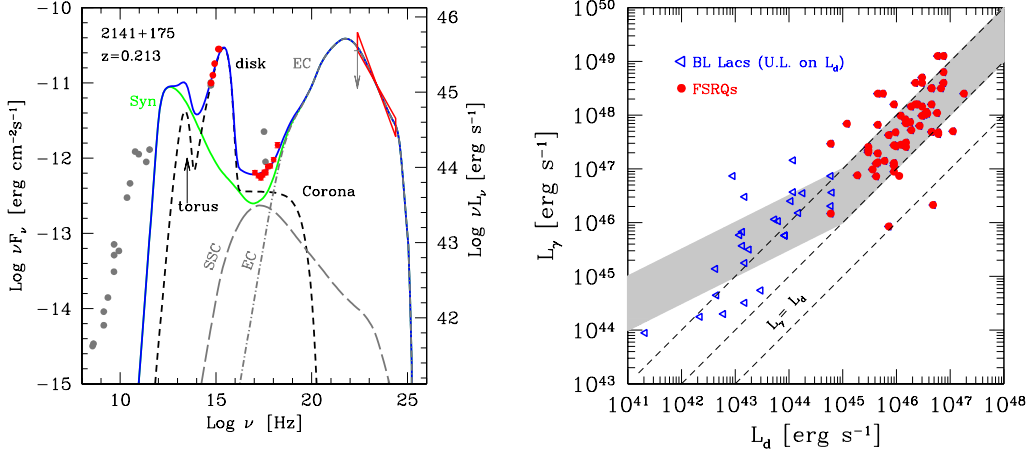


Figure 2. *Left panel:* the SED of the FSRQ 2141+175 and the fitting model. We label the different components. Note how the synchrotron spectrum, peaking at low frequencies, makes the accretion disk flux “naked”. In this cases the data are good enough for estimating both the black hole mass and the accretion rate. *Right panel:* the γ -ray luminosity as a function of the accretion disk luminosity for *Fermi* blazar of the A09 sample. Red filled circles are FSRQs, triangles are for BL Lacs with only an upper limit for their disk luminosity. The grey band corresponds to what expected if the FSRQs with $L_d > 10^{45} \text{ erg s}^{-1}$ have standard accretion disks with $L_d > 10^{-2} L_{\text{Edd}}$ and $L_\gamma \propto L_{\text{jet}} \propto \dot{M} \propto L_d$, while BL Lac have “ADAF” like accretion with $L_d \propto \dot{M}^2$. In this case their $L_\gamma \propto L_{\text{jet}} \propto \dot{M} \propto L_d^{1/2}$.

$L_d \sim 10^{-2} L_{\text{Edd}}$. In the near future, when blazars with black holes of smaller masses will be observed, this clear-cut division will become fuzzier.

2.1. Jet powers

Several attempts have been done in the past to find the jet power and the accretion disk luminosity in blazars and radio-loud objects in general (starting from Rawlings & Saunders 1991; Celotti et al. 1997; Cavaliere & D’Elia 2002; Maraschi & Tavecchio 2003; Padovani & Landt 2003; Sambruna et al. 2006; Allen et al. 2006; Celotti & Ghisellini 2008; Ghisellini & Tavecchio 2008; Kataoka et al. 2008). These works found large jet powers, often larger than the luminosity produced by the disk. However, there were two caveats: the first concerns the low energy end of the emitting particle distribution, where most of the electrons are. To the end of estimating the jet power, this is a crucial quantity if one assumes that there is one proton per electron (and this assumption is the second caveat). But in powerful sources, for which the radiative cooling is severe, even low energy electrons cool in a light crossing time, leaving much less uncertainty about the presence of low energy electrons, distributed in energy $\propto \gamma^{-2}$.

Sikora & Madehski (2000) and Celotti & Ghisellini (2008) argued that electron-positron pairs cannot be dynamically important, corresponding to a limit of a few pairs per proton. This issue (discussed at length in Celotti & Ghisellini 2008 and G09) can be understood looking at the left panel of Fig. 3,

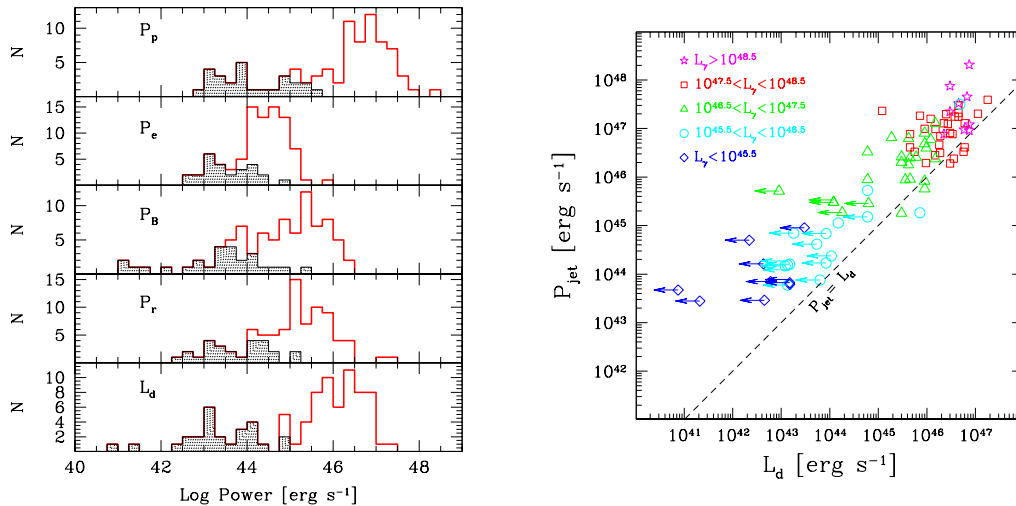


Figure 3. *Left panel:* The distribution of jet powers in the form of bulk motion of cold protons (P_p), emitting electrons (P_e), magnetic field (P_B) and radiation (P_r). The bottom panel shows the distribution of disk luminosities L_d . Grey shaded areas correspond to BL Lacs. *Right panel:* the total jet power P_{jet} vs the accretion disk luminosity L_d . To estimate P_{jet} , we have assumed one proton per emitting electron.

showing the histograms of the different forms of power carried by the jet. The shaded areas correspond to BL Lacs. The crucial power, that is almost model-independent, is the power P_r spent by the jet to produce its radiation. It is simply the observed, beamed, bolometric luminosity multiplied by $\Gamma^2/\delta^4 \sim 1/\delta^2$. For FSRQs, the distribution of P_r extends to larger values than the distribution of P_e , the power carried by the jet in the form of emitting electrons. So the radiation we see cannot originate by electrons (or pairs) only. Can it come from the Poynting flux (by e.g. reconnection)? The distribution of P_B is at slightly smaller values than the distribution of P_r , indicating that the Poynting flux cannot be at the origin of the radiation we see. As described in Celotti & Ghisellini (2008), this is a direct consequence of the large values of the Compton dominance (i.e. the ratio of the Compton to the synchrotron luminosity is small), since this limits the value of the magnetic field.

To justify the power that the jet carries in radiation we are forced to consider protons. If there is one proton per electron (i.e. no pairs), then P_p for FSRQs is a factor ~ 10 – 100 larger than P_r , meaning an efficiency of 1–10% for the jet to convert its bulk kinetic motion into radiation. This is reasonable: most of the jet power in FSRQs goes to form and energize the large radio structures, and not into radiation.

We then conclude that jets should be matter dominated, at least at the scale (hundreds of Schwarzschild radii from the black hole) where most of their luminosity is produced. The bottom left panel of Fig. 3 shows the distribution of the disk luminosities. In this case the shaded area corresponds to upper limit for BL Lac objects, and not to actual values. This L_d distribution lies at intermediate values between P_r and P_p .

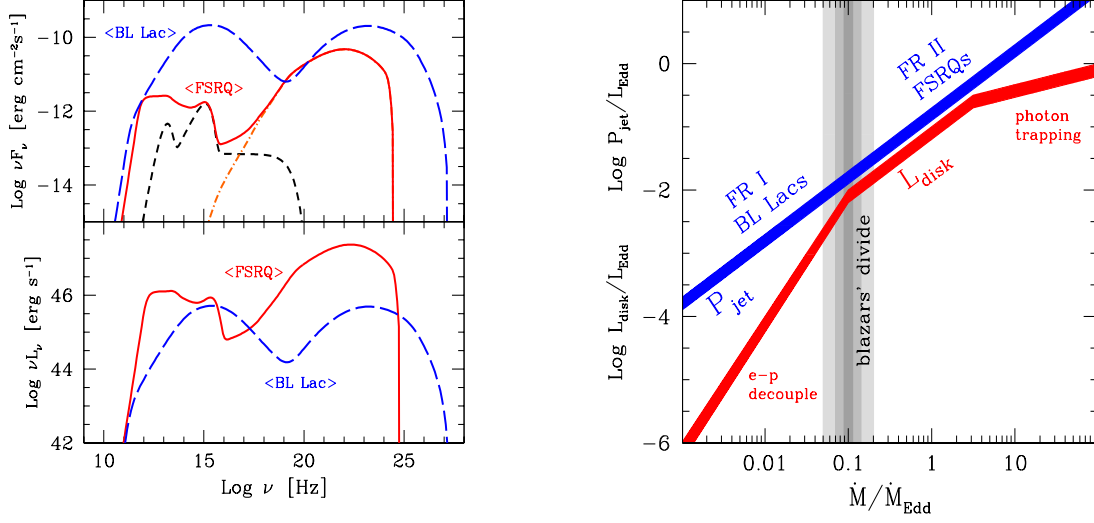


Figure 4. *Left panel:* The average SED for BL Lacs (blue long dashed), and FSRQs (red solid) detected in the 3-months *Fermi* survey, both in νF_ν (top) and νL_ν (bottom). *Right panel:* sketch illustrating P_{jet} and L_d as a function of $\dot{M}/\dot{M}_{\text{Edd}}$. It is assumed that the jet power always scales linearly with \dot{M} , while accretion rates below a critical value produce radiatively inefficient accretion disks. In this case the object looks like a BL Lac (if aligned) or a FR I (if misaligned). The gray stripes indicate the critical $\dot{M}/\dot{M}_{\text{Edd}} \sim 0.1$, producing the blazars' divide at $L_d/L_{\text{Edd}} \sim 10^{-2}$.

2.2. Jet powers and disk luminosities

The right panel of Fig. 3 shows the total jet power $P_{\text{jet}} \equiv P_p + P_e + P_B$ as a function of the thermal disk luminosity. Arrows corresponds to BL Lacs for which only an upper limit on L_d could be derived. The different symbols corresponds to blazars of different γ -ray luminosities, and one can see that L_γ correlates both with P_{jet} and L_d .

As discussed in G09, there is a significant correlation between P_{jet} and L_d for FSRQs, which remains highly significant even when excluding the common redshift dependence. The slope of this correlation is consistent with being linear, and P_{jet} is larger than L_d for almost all sources, and must be much larger for BL Lacs.

3. Discussion

The first results of *Fermi* confirm the idea that blazars form a sequence. Fig. 4 shows the average model SED constructed for BL Lacs and FSRQs by averaging the parameters obtained by fitting the sources one by one. It shows both the νF_ν and νL_ν representations. In the LAT energy range the average BL Lac has a flat ($\alpha_\gamma < 1$) spectrum, while FSRQs are steeper than unity. This is associated with the larger Compton dominance in FSRQs, in turn associated with the presence of external seed photons for the scattering process. Also shown (short dashed line)

is the averaged disk spectrum of FSRQs, together with the spectrum produced by the X-ray corona and the re-emission of part of the disk optical-UV radiation by an absorbing torus.

3.1. Relevance of the accretion rate

The relation between P_{jet} and L_{d} strongly suggests that

$$P_{\text{jet}} \approx \dot{M} c^2 \quad (1)$$

while the accretion disk luminosity

$$\begin{aligned} L_{\text{d}} &\sim 0.1 \dot{M} c^2 & \dot{M} &\geq \dot{M}_{\text{c}} \\ L_{\text{d}} &\sim 0.1 \left(\frac{\dot{M}}{\dot{M}_{\text{c}}} \right)^2 c^2 & \dot{M} &\leq \dot{M}_{\text{c}} \end{aligned} \quad (2)$$

where the $L_{\text{d}} \propto \dot{M}^2$ dependence is appropriate for advection dominated accretion flows (ADAF, e.g. Narayan, Garcia & McClintock 1997). Radiatively inefficient disk may also correspond to adiabatic inflow-outflows (ADIOS, Blandford & Begelman 1999) or a convection dominated flows (CDAF, Narayan, Igumenshchev & Abramowicz 2000). At the other extreme of accretion rates (i.e. nearly Eddington) the density close to the hole may correspond to scattering optical depths larger than unity, trapping a fraction of photons and making them to be swallowed by the black hole before escaping. Fig. 4 sketches the expected behavior of both P_{jet} and L_{d} as a function of $\dot{M}/\dot{M}_{\text{Edd}}$, where $\dot{M}_{\text{Edd}} \equiv L_{\text{Edd}}/c^2$. According to this scenario all radio loud objects of all powers have a jet power proportional to \dot{M} , irrespective of the accretion regimes. These instead affect the emitted disk luminosity L_{d} at both ends of the \dot{M} range. Below $L_{\text{d}} \sim 10^{-2} L_{\text{Edd}}$, corresponding to $\dot{M} \sim 0.1 \dot{M}_{\text{Edd}}$, the disk becomes radiatively inefficient, its ionizing radiation is greatly reduced, as are the broad lines. These objects are BL Lacs if pointing in our direction, and FR I radio-galaxies if they point somewhere else. Above the critical \dot{M} , jet powers and disk luminosities scale linearly, producing a FSRQ or a powerful FR II.

3.2. What powers blazars' jets?

The fact that the jet power correlates with L_{d} , but tends to be larger than that, leads us to ask: What is the source of the power of the jet? Is it only the gravitational energy of the accreting matter or do we necessarily need also the rotational energy of a spinning black hole? In G09 we have discussed two possible alternatives.

The first possibility stems out from the idea by Jolley et al. (2009) and Jolley & Kuncic (2008), who propose that, in jetted sources, a sizeable fraction of the accretion power goes to power the jet. As a result, the remaining power for the disk luminosity is less than usually estimated by setting $L_{\text{d}} = \eta \dot{M}_{\text{in}} c^2$, with $\eta \sim 0.08$ – 0.1 . This implies that the mass accretion rate needed to sustain a given L_{d} is *larger* than what we have estimated. Also the total accretion power is larger, and it is sufficient to explain the derived large jet powers.

The second alternative is the more standard Blandford & Znajek (1978) scenario, in which jets are powered by the rotational energy of the spinning black

hole. In this scenario the correlation between jet power and disk luminosity is provided by the requirement of having a sufficiently strong magnetic field, anchored to the disk, to tap the spin energy of the hole. If the magnetic energy density scales with the disk density, in turn linked to the accretion rate, then P_{jet} should scale as L_{d} .

Acknowledgments. I gratefully thank my collaborators A. Celotti, L. Foschini, G. Ghirlanda, L. Maraschi and F. Tavecchio. I thank the grant PRIN-INAF 2007 for partial funding.

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